SUPPRESSION EFFECTIVENESS SCREENING FOR IMPULSIVELY DISCHARGE AGENTS

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INTRODUCTION

Agent suppression effectiveness is typically measured by experiments in quasi-laminar diffusion flames established in a cup burner or counter-flow burner [1]. Those experiments are conducted by increasing the agent flow slowly until a critical mole fraction is achieved in the oxidizer and flame extinction is observed. In practice, however, agents designed to replace CF_3Br are discharged rapidly, not quasi-statically. Solid propellant gas generators (SPGGs), for example, typically discharge in 10 ms to 500 ms. A robust and repeatable means to evaluate the effectiveness of different formulations and burning rates is required, something that is impossible with conventional screening devices.

Hirst, Dyer, and coworkers developed a wind tunnel to explore the impact of step height, air flow, pressure, and agent mass requirements on the suppression of a pool fire [2,3,4], and concluded that liquid pool fires established behind an obstacle are highly challenging to extinguish. Hamins et al. [5] developed a phenomenological model to characterize the stability of baffle stabilized fires. Takahashi et al. [6] examined the character of methane/air flames for varying air velocity and baffle step height, and measured the amount of halon 1301 required to suppress the flames as a function of the flow parameters and injection interval.

The transient-agent recirculating-pool-fire (TARPF) suppression facility was designed to screen the performance of agents that are applied suddenly and for a short duration. The TARPF facility, originally described at the 1999 Halon Options Technical Working Conference [7], consists of a horizontal wind tunnel designed to simulate challenging fire situations and to precisely control the air flow, amount of agent , discharge rate, and discharge duration. Air is metered through a sonic orifice to overcome the unintended disruption that occurred in some previous studies during the agent discharge period. The influence of common geometric complexities (baffles, a backward-facing step and a cavity) on flow field dynamics and flame stability and a relationship between the mass of agent necessary for suppression and the agent injection duration are described in a paper by Grosshandler et al. [8] Direct numerical simulation of flame suppression is used in that paper to help explain the observations.

The capability to test solid-propellant gas generators has been added to the TARPF. For the first time, both compressed and solid-propellant generated gases can be compared side by side. It is now possible to discriminate among formulations, particle loadings and burning rates for various

SPGG designs. The SPGG injection system and measurement method are described in this paper, and the results from experiments with a commercial air-bag gas generator are presented.

EXPERIMENTAL FACILITY

The TARPF facility, shown schematically in Fig. 1, consists of a 2.5 m long steel duct with a square cross section 92 mm on a side. A compressor supplies dried ambient air, which is monitored using a calibrated sonic orifice and a piezoelectric pressure transducer. A diffuser (with a 12^{o} half-angle expansion) provides a smooth transition from the 38 mm diameter air line to the square duct. A honeycomb flow straightener and mixing screens are located downstream of the diffuser. A 26 mm high, 0.3 m long stainless steel ramp is located just before the burner. The burner is located on the floor of the duct, directly downstream of the ramp, and consists of a sintered bronze plate, 92 mm wide by 190 mm long. Commercial grade propane, metered by an electronic mass flow controller, is the fuel. The sintered metal plate is cooled by water flowing through copper tubes. The flame is viewed from above and the side through glass windows. A photograph of the facility is shown in Fig. 2.

The flame is ignited by a spark across two protruding electrodes located on the side wall of the test section 20 mm above the surface of the burner and 20 mm downstream of the step. A plate inserted into the flow from the bottom surface of the duct directly downstream of the burner creates a cavity and can act as a possible source for reignition. A 30 Hz video camera records the flame and suppression process. For some experiments, a high speed digital camera (1000 Hz) is used to investigate the suppression dynamics.

Compressed Gas Agent Injection

Nitrogen (0.99995 mole fraction pure) and CF_3Br (commercial grade) are stored as gases in one and two liter stainless steel vessels with the pressure monitored by a high speed (1 ms response) piezoelectric transducer, and the temperature is measured with a chromel-alumel (76 mm diameter) thermocouple.   An electronic timer controls the interval (10 ms to 1000 ms) that a solenoid valve on the agent vessel remains open. The agent passes through a 6 mm diameter orifice before it is injected through two opposed radial ports into the air passage upstream of the diffuser. A computer monitors the flow controllers, pressure transducers, and thermocouples, and sends a signal to the electronic timer to open and close the solenoid valve while releasing the flow of suppressant. Pressure and temperature in the agent storage vessel are measured at a frequency of 1000 Hz during the discharge process.

The mass of the gaseous agent released is determined from the change in pressure and temperature in the storage vessels [5]. The expanded uncertainty in the calculated mass is ± 2 %, with a minimum absolute uncertainty of 0.12 g attributable to the resolution of the pressure transducer. (Note that this and all other quantified uncertainties are for a coverage factor of 2 unless stated otherwise.)   From the temperature and pressure measurement, the rate of suppressant addition to the incoming air, *dm/dt*, can be estimated within an expanded uncertainty of ± 2 g/s.

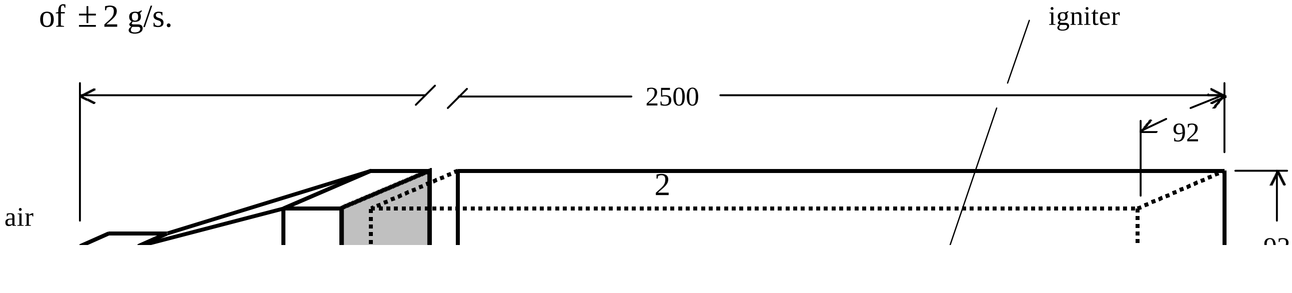

Figure 1. Schematic of step-stabilized pool fire apparatus. Dimensions are in millimeters.

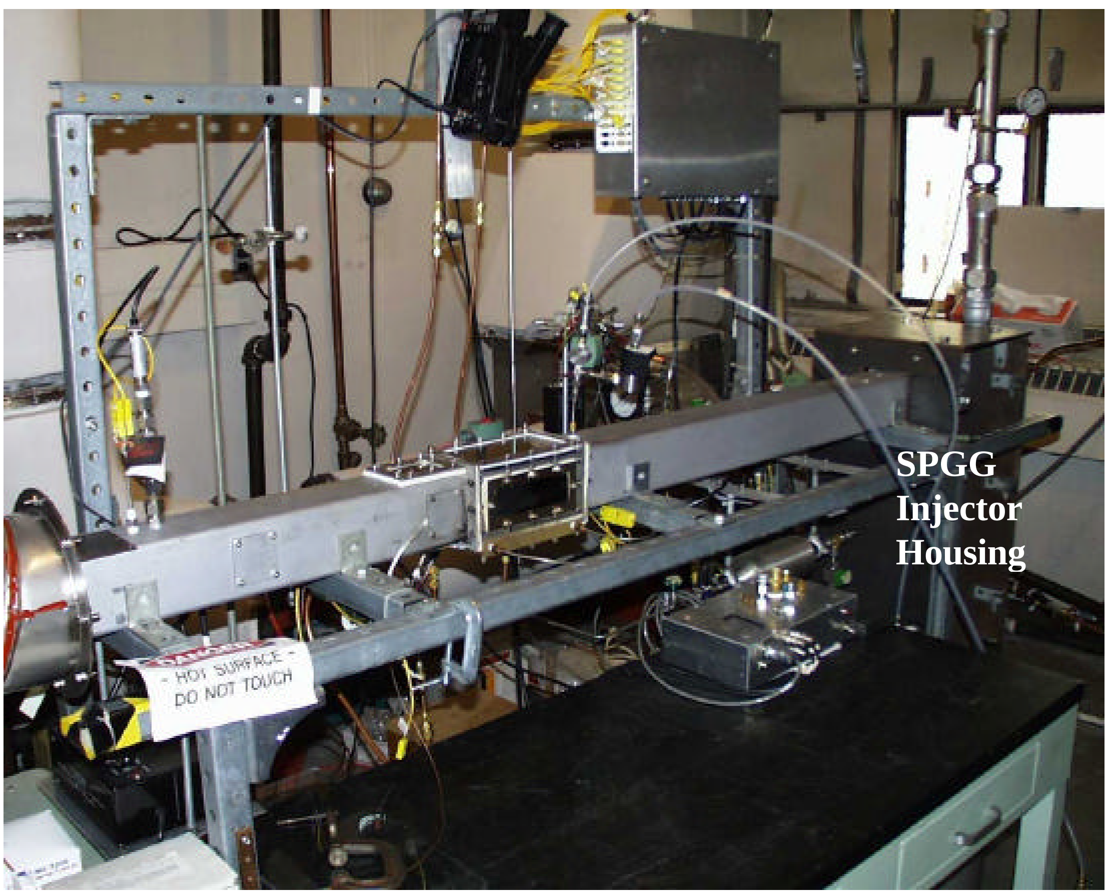

Figure 2. Photograph of TARPF showing location of SPGG injection system

SPGG Injection System

Gas generators are manufactured in discrete units with a pre-determined burning time. Unlike the compressed gas injection system described above, neither the total mass burned nor the injection time interval can be controlled after the units are manufactured. To accommodate this limitation, a custom discharge chamber was designed to allow the operator to select the fraction to be injected into the flame zone. The chamber is made of stainless steel with an internal volume of approximately 200 mL. There are four ports on the chamber as shown in Fig. 3: (1) a gas generator inlet port with 3/4 NPT female thread, (2) a small metering orifice (1.6 mm to 6.4 mm diameter) to limit the flow into the TARPF, (3) a large bypass port (25 mm to 50 mm diameter), and (4) a 19 mm blow-out port. By selecting the appropriate areas for the metering orifice and bypass port, the fraction of the flow injected into the fire zone can be varied. This feature permits standard size gas generators (which normally contain significantly more material than is required for suppression in the TARPF) to be evaluated by repeating the test sequence with identical gas generators and increasing the bypass ratio in small increments. The gas and/or powder that passes through the metering orifice is injected into the air stream (see Fig. 3) using the same manifold as is used for the compressed gas agent.

In the lower portion of Fig. 3 is a vertical capped pipe, 50 mm in diameter, that houses the gas generator. For the current experiments, fifty identical commercial air-bag hybrid gas generators were used, each releasing 20.7 g $\pm$ 0.1 g of agent. Twenty grams of compressed argon gas is expelled from the unit by 0.7 g of propellant, which at equilibrium converts to KCl dust, H_2O, N_2 and a small amount of gaseous CO_2. An ignitor wire is attached to the bottom of the generator. A 6 mm thick steel cover is bolted to the box that encompasses the entire injection system as a precaution against a premature or explosive discharge. (Refer to Figs. 2 and 3.) SPGG cartridges can be changed and prepared for the next run within a few minutes.

EXPERIMENTAL RESULTS

Characterization of the TARPF facility (including a discussion of measurement uncertainty) has been described previously [7,8]. For the current experiments, the nominal velocity of the air above the backward-facing step was maintained constant at 5.4 m/s; the propane flow was 85 mL/s (at standard temperature and pressure). The flame created above the propane pool corresponds to what Takahashi et al. [6] describe as transitional between a rim-stabilized flame (regime I) and an intermittent turbulent flame (regime II).

The N_2 and CF_3Br suppression experiments were conducted earlier and the results presented last year [7]. The current study was directed towards evaluation of the SPGG injection system. The pressure build-up in the discharge chamber was measured for a range of bypass areas, as seen in Fig. 4. The high pressures produced in the chamber and the known area of the metering orifice allow the mass flow of agent added to the air stream of the TARPF to be estimated by assuming that the flow through the orifice is choked. Figure 5 shows the repeatability of the agent injection process with five overlaying mass flow and thermocouple temperature traces. (The thermocouple does not reflect the true gas temperature, which is expected to be hundreds of

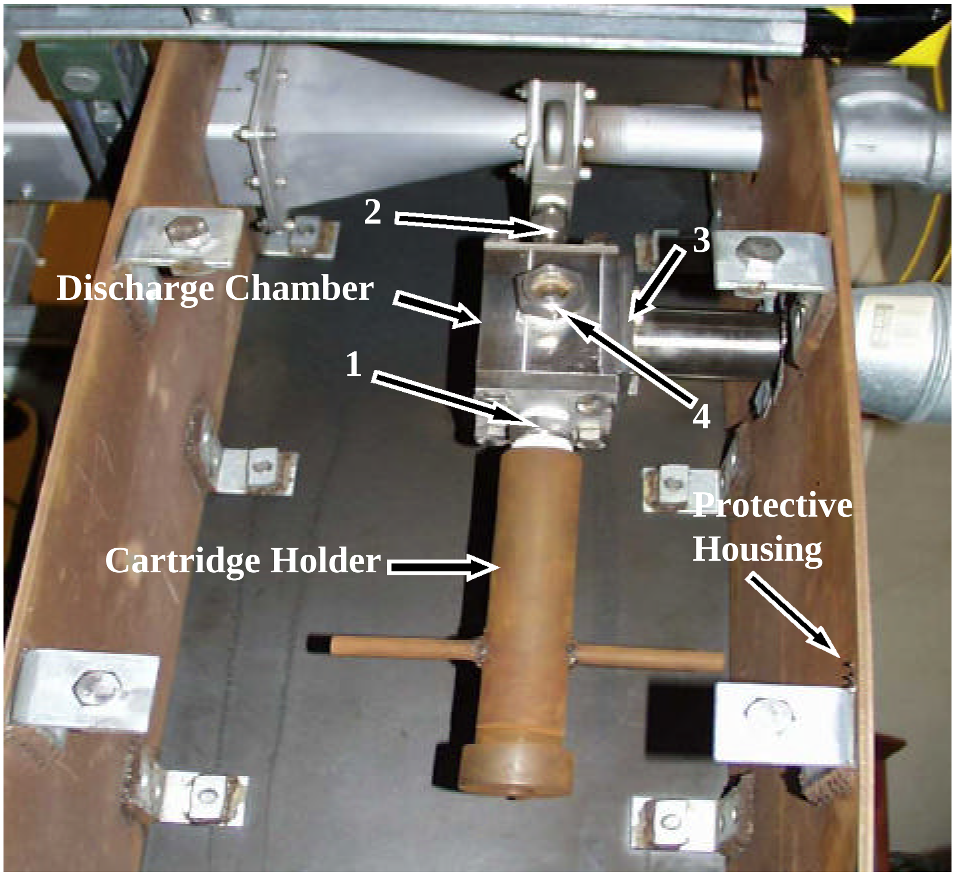

Figure 3. Photograph of SPGG injection system showing cartridge holder, discharge chamber, and ports: (1) SPGG outlet, (2) metering orifice, (3) bypass, and (4) blow-out.

degrees Celsius hotter than recorded in the figure.)

The discharge time was consistently 20 ms $\pm$ 1 ms, which is over three times faster than the shortest N_2 or CF_3Br injection interval, and not much affected by the bypass port area. The time interval, *Dt*, is shown in Fig. 6 as a function of the ratio of the metering orifice area to the total open port area, times the total mass loss of the SPGG. The total mass delivered to the air stream during the discharge process is found by integrating *dm/dt* over *Dt*. Excluding the highest and lowest area ratios, the estimated mass delivered can be seen in Fig. 6 to be linearly proportional to the area ratio; however, almost 50 % more mass is estimated than one would expect. The dashed line in Fig. 6 indicates the 1-to-1 relation that would exist if the mass were directly proportional to the area ratio.

There are several factors that contribute to an uncertainty in the estimate of the absolute mass of agent.   First, uncertainties in the gas composition and temperature upstream of the metering orifice affect the estimate since the mass is proportional to the square root of the molecular weight divided by the temperature. A factor of two under-estimate of this parameter would cause a 40 % over-estimate in mass, which, if corrected for, would cause the data plotted in Fig. 6 to more closely align with the dotted line. A second source of uncertainty is the complexity of the

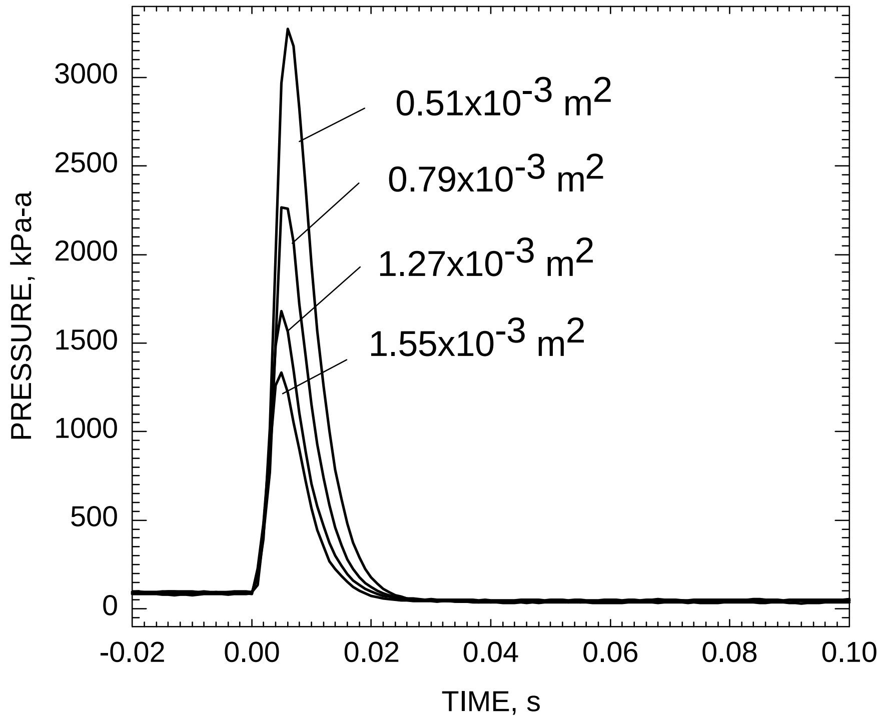

Figure 4. Chamber pressure created by SPGG discharge as a function of bypass area.

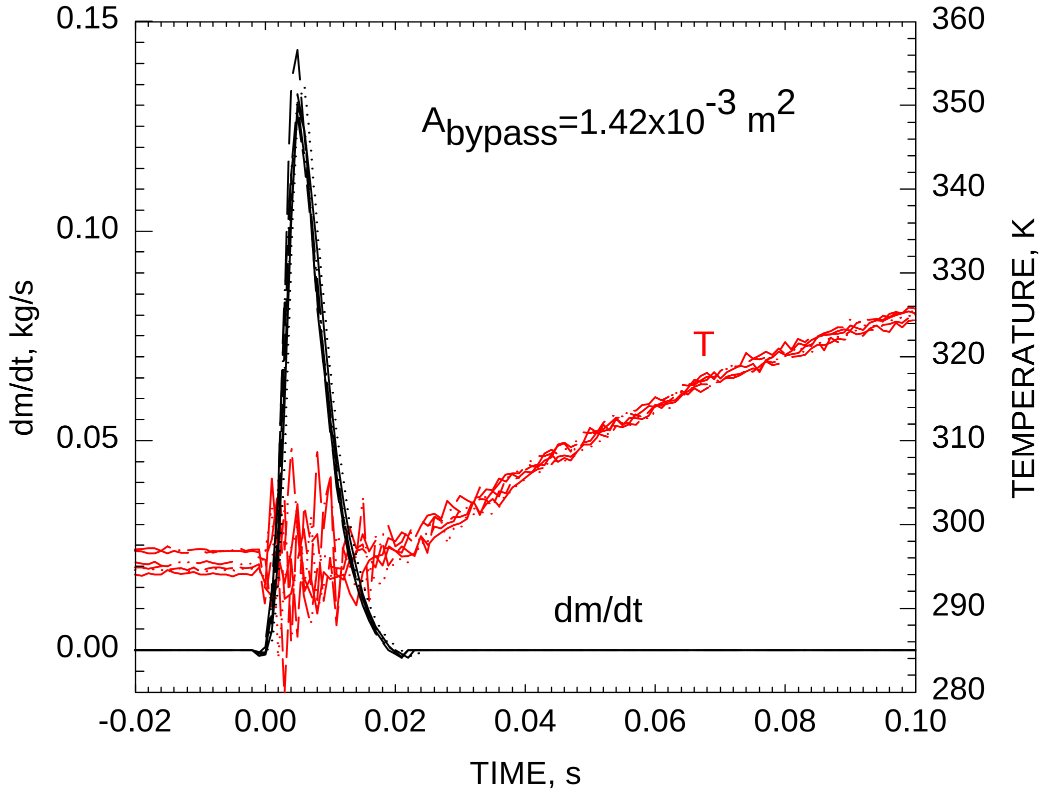

Figure 5. Discharge chamber thermocouple temperature and estimated mass flow of SPGG efluent added to air stream for multiple identical runs.

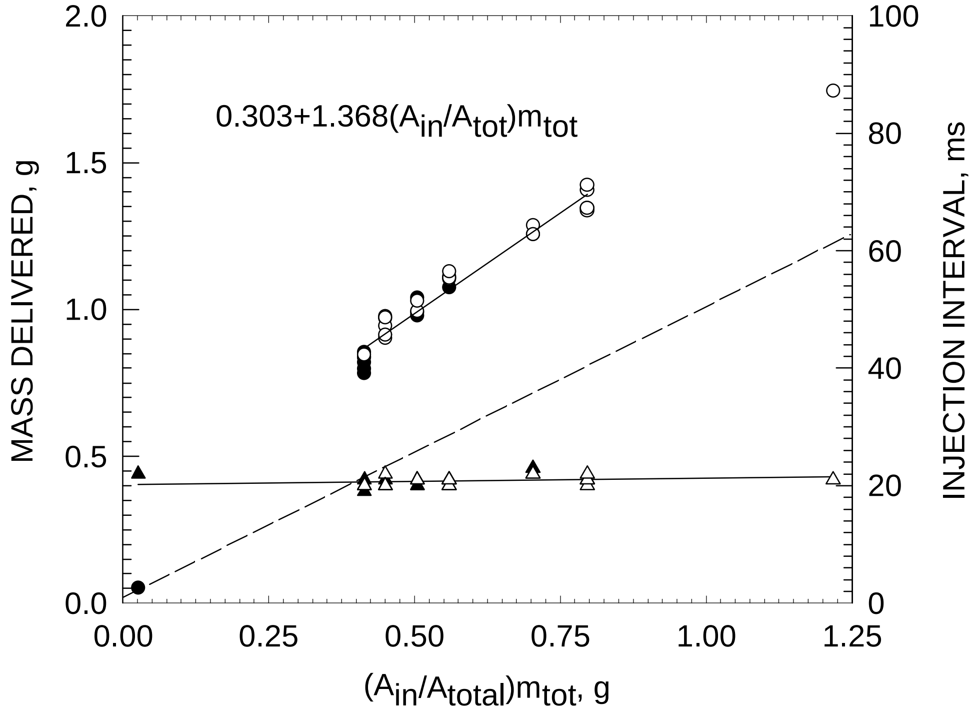

Figure 6. Injection interval (triangles) and calculated mass delivered to flame (circles) as a function of area ratio times total mass of gas generated (20.7 g).

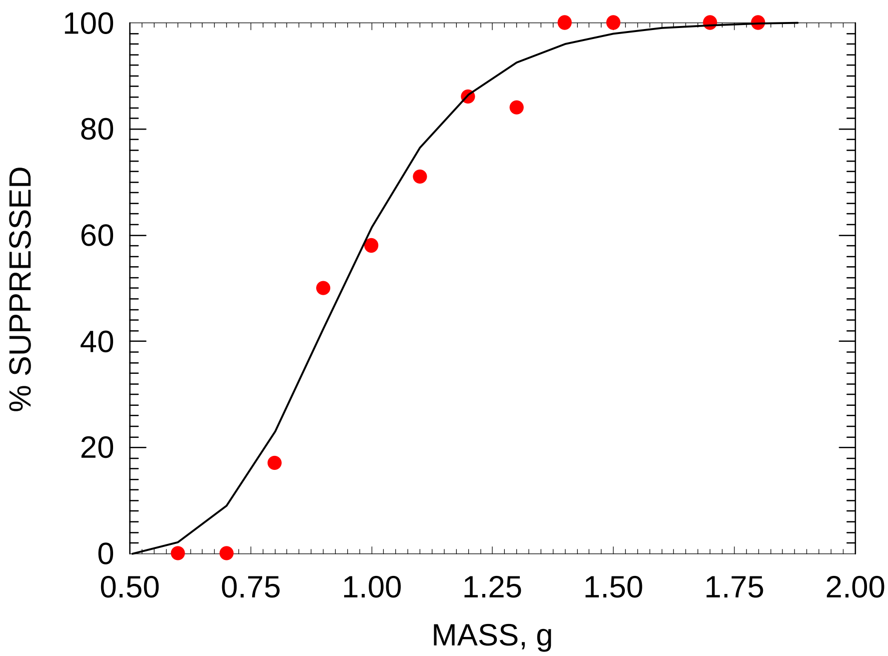

Figure 7. Percentage of flames extinguished as a function of mass delivered to flame by SPGG.

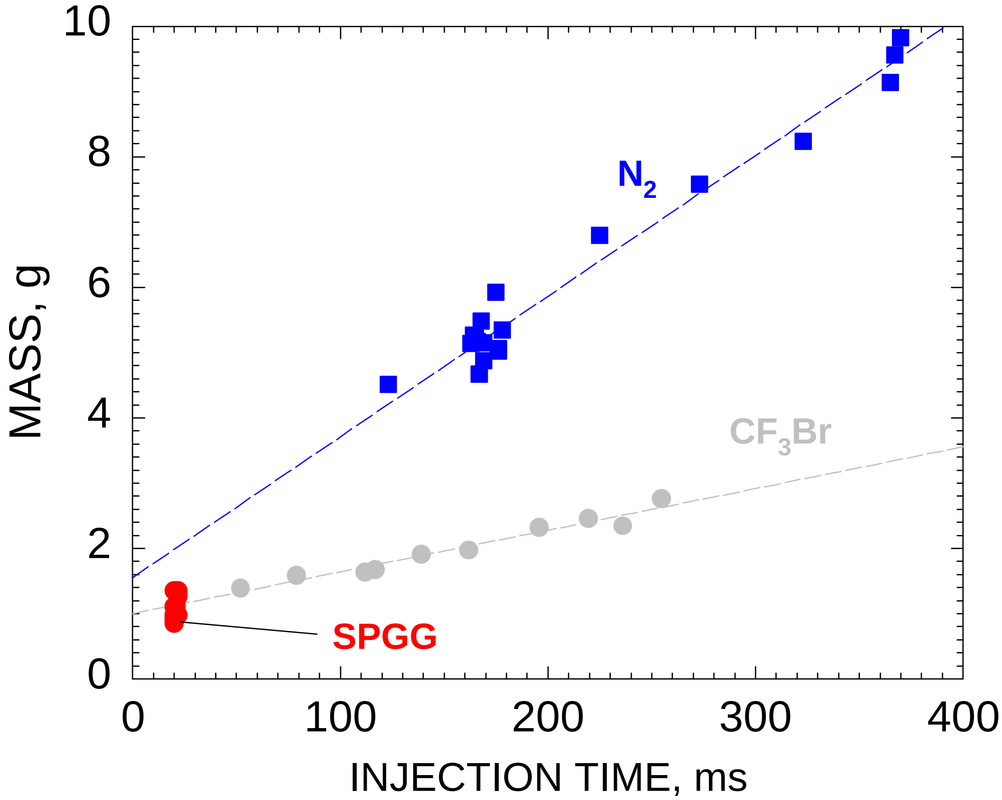

Figure 8. Impact of injection time interval on the mass of agent (CF_3Br, N_2, or SPGG) required to suppress step-stabilized propane pool fire.

flow within the discharge chamber created by the jet emanating from the SPGG. The calculation assumes the upstream flow is steady and parallel to the axis of the metering orifice, but the flow is highly transient and more perpendicular.

Suppression of the propane pool fire with the hybrid gas-generators was found to be successful if at least 1.5 g of agent was injected into the fire; conversely, extinction never occurred when less than 0.7 g was added. The percent of the fires suppressed varied when the agent mass was between these limits, as shown in Fig. 7. The suppression statistics were generated by lumping the mass from thirty-three discharges into bins 0.2 g wide, centered about the data plotted. The solid line is a fit to the data assuming the shape is sigmoidal. From the curve, one can see that there is a 50 % chance that suppression will be successful if the amount of agent is 0.9 g $\pm$0.1 g, and there is a 90 % success rate for 1.3 g $\pm$0.1 g of agent.

Figure 8 is a plot of the mass of agent required for suppression versus the injection time interval. All of the SPGG data are lumped around 20 ms since the injection time was fixed. The N_2 and CF_3Br results extend to much longer injection time intervals. Linear fits to the data yield intercepts of 1.6 g for nitrogen and 1.2 g for halon 1301. The SPGG data fall close to the halon results. The significance of the linear shape and value of the intercept is unclear; however, the superior performance of the gas generator is undeniable.

The mass fraction of agent, beta, is defined as the total mass injected divided by the *Dt*, over the sum of the mass flow of air plus the mass flow of agent. The percent time that the flame was extinguished is plotted in Fig. 9 as a function of beta. All of the fires were extinguished when β was greater than 0.62; none for a mass fraction below 0.49.

Data Correlation

A characteristic time, τ, for mixing of the agent into the flame zone can be defined in terms air and agent volume flows, $(V'_{air} + V'_{agent})$, and the step height, h, as

$$\tau = \gamma h / \{(V'_{air} + V'_{agent})/[(L-h)L]\} \tag{1}$$

where L is the width of the tunnel and γ is an empirical non-dimensional parameter that relates the ratio of the distance that a fluid element travels within the recirculation zone to the obstacle height. The recirculation zone behind a backward step (with no combustion) is typically 8 to 10 times the height of the step. Thus, the distance traveled in a single circumnavigation of the recirculation zone should be about twice this amount, or 16 to 20 step sizes. Evaluating Eq. (1) for the conditions examined in the current study and using a value of 20 for γ, τ is found to vary between 0.03 s and 0.07 s.

Hamins et al. [5] found that for a specified injection duration it is possible to relate the mole fraction of agent required to achieve extinction, X, to the characteristic mixing time, τ, according to the following relation:

$$X/X^* = [1-\exp(-Dt/\tau)]^{-1} \tag{2}$$

where X^* can be found experimentally by flowing agent continuously into the air stream at increasing rates until extinction occurs. If the air flow is low enough, the value of X^* is expected to be similar to the cup burner extinction requirements [5].

For heptane, Trees et al. [1] found the value of X^* to be 0.32 for N_2, 0.41 for Ar, and 0.031 for CF_3Br. For laminar diffusion flames strained at intermediate rates, Trees et al. [1] showed that the minimum extinction mole fraction of agent in a counterflow flame decreases from the cup burner value when the strain rate is 50 s^{-1} to much smaller values for a strain rate of 400 s^{-1}. Although the flow in the recirculating region behind a step is much more complicated than in a counterflow flame, the strain rate in the current study should scale with $1/\tau$. When the flow of air is increased sufficiently, the flame becomes strained to the point that agent is not needed for extinguishment (i.e., $X^* \rightarrow 0$) and the flame blows out.

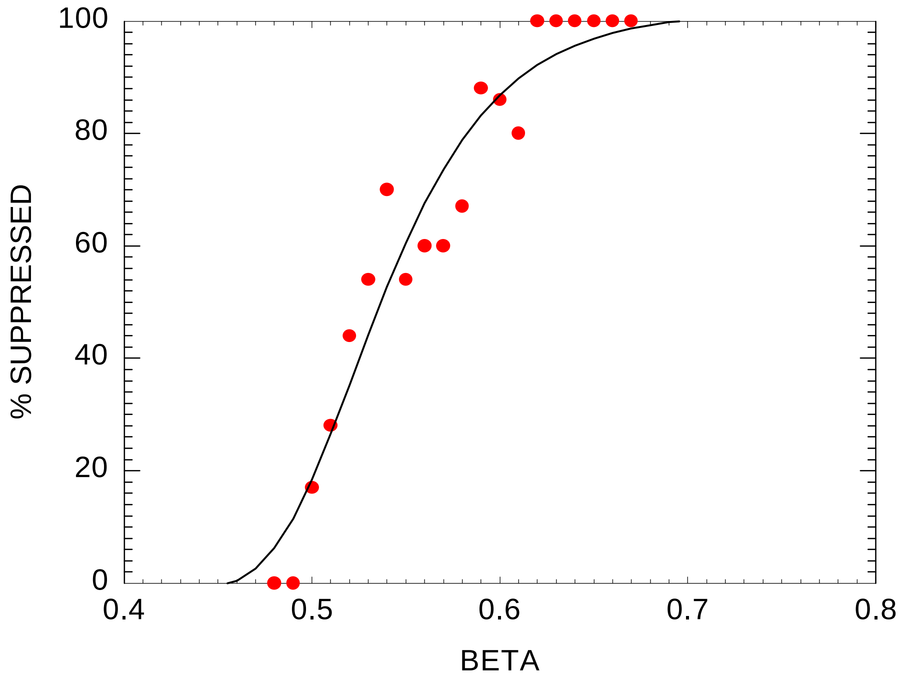

Figure 9. Percentage of flames extinguished as a function of the estimated mass fraction of agent

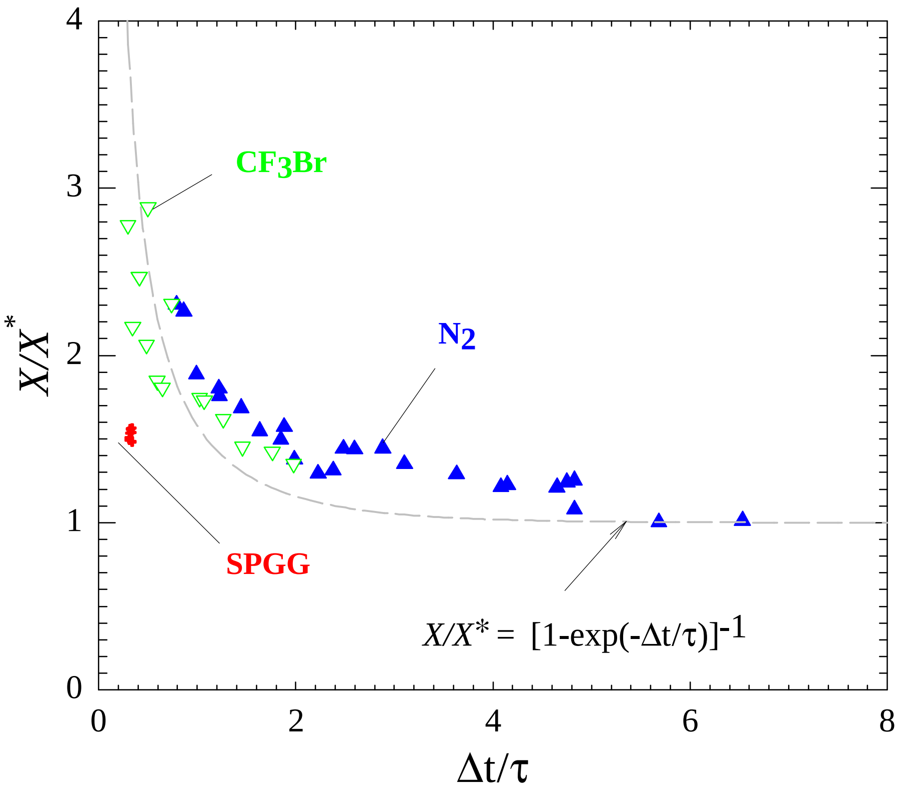

Figure 10. Normalized mole fraction as a function of non-dimensional injection interval, comparing N_2, CF_3Br, and SPGG

The extinction mole fraction data have been normalized by their respective cup burner values (the SPGG is assumed to be pure Ar), and are plotted in Fig. 10 as a function of the injection time interval divided by the respective values for τ. The data for the SPGG represent a 50 % to 90 % chance that suppression is attained. Equation (2) is shown as the dotted line. Even when viewed this way, clear distinctions remain among N_2, CF_3Br, and the SPGG. The chemical advantage of the halon over nitrogen is evident. Why the performance of the SPGG is so superior is not understood since the impact of very short addition times should be accounted for by non-dimensionalizing the process. The existence of KCl powder is expected to increase the suppression effectiveness of the SPGG formulation (Ewing [9] suggests a cup burner mass fraction of 0.038 for KCl), but the small amount present is unlikely to explain the behavior by itself.

SUMMARY AND CONCLUSIONS

A transient application, recirculating pool fire (TARPF) facility has been built for screening the suppression effectiveness of halon 1301 replacements. Nominal air velocities between 2 m/s and 23 m/s flowing over a backward-facing step were examined. Because the air is metered with a sonic orifice, the injection of agent does not modulate the air flow. The minimum amount of agent for flame extinguishment is substantially and directly affected by the air velocity and the interval of injection. A simple mixing model is useful to explain the observed trend of decreasing suppressant mole fraction with increasing injection duration. Several areas, however, require further investigation including the effect of the air flow on the steady-state extinction mole fraction of agent, the relationship between agent injection and its concentration history at the flame, and especially the observed differences in the normalized mole fractions of CF_3Br, N_2, and the SPGG for very short injection time intervals.

The ability to measure the relative effectiveness of alternative agents is key to the development of new fire suppression systems. The physical and chemical properties, and the manner of storage and release of the next generation suppression systems may be quite unlike CF_3Br, but their effectiveness must still be bench-marked against it. The TARPF facility provides the means to screen gaseous agents and solid propellant gas generator concepts in the laboratory for applications in protected spaces involving baffle-stabilized pool fires.

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